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**ADVANCED YBCO-COATED CONDUCTORS FOR USE
ON AIR PLATFORMS (POSTPRINT)**

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**Power Generation Branch
Power Division**

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Advancing YBCO-Coated Conductors for Use on Air Platforms

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With progress of the YBCO-coated conductor to longer lengths, application of the conductor is nearing. An overview of a couple of current U.S. Air Force application programs is presented. A discussion is then made of where research and development of the YBCO-coated conductor should progress and examples in the U.S. Air Force program. These areas include magnetic flux pinning in YBCO thin films, reduction of the ac losses experienced in the YBCO conductor, and stability and quench issues when implementing the YBCO-coated conductor.

Introduction

As aircraft systems become more electrically driven, there is a need for greater electrical power. Some of these systems reach the multimegawatt level. However, on aircraft the power-generation subsystems must be as lightweight and low volume as possible, allowing as much of the limited payload and space for either the primary systems or mission. Whether it is the power-generation system or some other component, reduction in weight and/or size is highly desired. This is especially true in the U.S. Air Force. Consider the power-generation issue. Conventional power generation has been extensively developed and optimized, but these generators cannot provide multimegawatt amounts of power without placing an undesired burden on payload and space. Advanced development of compact, lighter, conventional power-generator systems often sacrifices system efficiency and lifetime in addition to reducing

the duty cycle. A lower duty cycle, from 100%, means that the generator can only be on for a limited time and must be turned off for a another length of time before resuming power. If this fits the need, then this is not an issue; however, limitations of the generator should not dictate the mission parameters. Superconducting components, such as generators, can provide the reduction in weight and/or size without sacrificing these parameters.^{1,2}

Because of the advantage of superconducting systems, the development of a high-temperature superconducting (HTS) wire is being pursued. These HTS conductors typically take the form of a thin flat tape as opposed to a round wire. Even so, the HTS tape allows the conductor to be bent around fairly small diameters to create high-density coil and magnet windings. The first HTS conductor to be scaled and applied to applications was the bismuth strontium calcium copper oxide (BSCCO) superconductor. However, because the superconductor is embedded in a silver matrix material, which can occupy over half the volume of the wire, the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO)-coated conductor (or

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where other rare earths substitute for yttrium) is now being more aggressively pursued. YBCO has several significant advantages over the BSCCO wire: in-field operation at liquid nitrogen temperatures while maintaining critical currents (J_c) $> 10^5$ A/cm² in magnetic fields up to several Tesla, the ability to reduce ac losses in the architecture, improved strain tolerance, and lower production costs. Advances in the YBCO-coated conductors have resulted in improvements in the quality and length of wire available—from 10^5 A/cm² at several centimeter lengths just a few years ago to lengths up to 300 m with 10^6 A/cm² performance^{3,4} as per news releases by American companies in 2006 (references are the most recent publications). These successes have been achieved principally focusing on the primary architectural components of the conductor.

With the above-mentioned progress and continuous processing of the YBCO conductor well underway, this paper first provides a couple of U.S. Air Force application examples in progress for the HTS conductor and then discusses where the focus of the YBCO conductor research should be headed and recent progress in U.S. Air Force programs, especially as related to these systems and in light of research efforts in a variety of nonmilitary programs. As such, research and developmental areas to be discussed are magnetic flux pinning in YBCO thin films, reduction of the ac losses experienced in the YBCO conductor, and stability and quench issues when implementing the YBCO-coated conductor. A more thorough review of the history of the power-generator development, benefits of superconducting systems, and associated YBCO conductor issues is given by Barnes *et al.*¹

Applications—Directed Energy

Use of superconducting technologies in the U.S. Air Force can address the weight/size concerns. One example of this is directed energy weapons (DEW). One specific DEW technology being developed is active denial technology (ADT).⁵ ADT is a nonlethal airborne DEW that will require the benefits of compact power generation. In addition to the generator, the associated gyrotron magnet is also superconducting; the magnet is currently wound with low-temperature superconductors. There are also other applications for the U.S. Air Force, Navy, and Army requiring large amounts of power; for example, the Navy has programs on both

homopolar and synchronous superconducting motors to drive the future all-electric ship.⁶ Westinghouse has, in the recent past, conducted work sponsored by the Ballistic Missile Defense Office (BMDO) to provide high power for a mobile radar.⁷

Multimegawatt Electric Power System

The Power Division of the Air Force Research Laboratory Propulsion Directorate is managing a superconducting generator program with General Electric entitled the Multimegawatt Electric Power System (MEPS). The MEPS program was awarded to General Electric at the end of 2004, and the initial demonstration generator is currently being built. The intent per the program announcement is to advance the power technologies in support of DEW being placed on airborne platforms. Specifically, with the large onboard electrical power demands, it is necessary to develop the required power generation, distribution, and conditioning technologies required for the airborne use of these weapons. The Broad Agency Announcement for the program stated that the specific objective of the MEPS program is the development and testing of a superconducting power system for airborne-directed energy weapons. The power system includes a gas turbine drive, a superconducting generator, and a power conditioning system. Although a complete power system will be made, emphasis of the effort is geared toward the superconducting generator. An initial demonstration of the generator is planned for the end of 2007 and a full-power demonstration of the complete power system by the end of 2009.

For the program, General Electric proposed a synchronous, homopolar, inductor-type alternator with a stationary HTS coil, solid rotor forging, and conventional stator; refer to Fig. 1. This is not the typical ac synchronous generator scheme generally considered when thinking about superconducting generators, and provides a new perspective to superconducting generators. There are trade-offs between the approach being used by General Electric and the typically used superconducting generator scheme, but these will not be discussed in detail here. Because this paper is focused on the HTS application and how this drives the superconductor's development, only the uniqueness of the General Electric approach will be discussed—refer to Barnes *et al.*¹ for additional information on the basic ac synchronous superconducting approach.

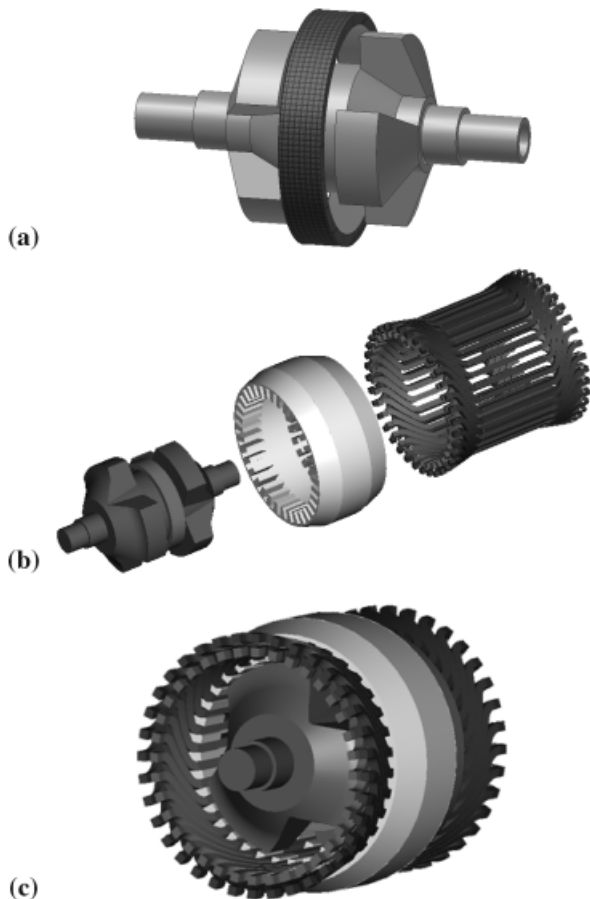


Fig. 1. Schematics of the generator parts developed by General Electric in the multimewatt electric power system program: (a) high-temperature superconducting (HTS) coil (red) around the solid forged rotor (gray) with offset poles; (b) from left to right the HTS coil and rotor (from a), the stator yoke, and the armature windings; (c) the parts from (b) assembled.

Generally, the superconducting field windings are integrated into the high-speed rotor, but in this design the HTS coil is stationary. Magnetic flux is carried through a solid-forged rotor to generate the current in the armature windings. The maximum flux that can be carried through the rotor depends on the choice of the soft magnetic material used and the rotor is spun faster to compensate for this limitation. Because the HTS coils are not in the rotor proper, this avoids the issue of high-speed rotating cryogenic seals for cryogen transfer to and from the spinning rotor. It also more efficiently segregates the HTS coil from other components, making thermal isolation of the HTS coil simpler. This also

reduces the refrigeration system and makes the transfer lines less complex with better thermal stability. The design also provides improved quench protection of the coil because it has low-stored energy and allows a simplified HTS magnet support structure. The advantage of using the HTS coil instead of low-temperature superconducting (LTS) windings is that the refrigerator's composite weight/power/size is reduced 20–50 times over the 4 K variant.

Gyrotron Magnet

Another consideration for DEW with respect to superconducting components is the gyrotron magnet. High-field magnets are necessary to generate high-power electromagnetic radiation. Because of this, LTS magnets are currently used in the gyrotron. Developing an HTS magnet to replace the LTS magnet can substantially reduce the refrigeration load. With the HTS conductor operating at 60–77 K (as opposed to 4.2 K), it would result in more than an order of magnitude reduction and almost two of the associated cryocooler. Any weight or size reduction is important as well as a decrease in cooldown times, which is possible at higher temperatures. Cryomagnetics has already made an HTS gyrotron magnet out of an HTS BSCCO conductor and currently has a program to make a YBCO gyrotron magnet. Superconducting components are possible other than the beam-shaping magnets as presented by Oberly *et al.*⁸ YBCO beam spreader magnets may be possible. In this case, an ac-tolerant version of the superconducting wire is necessary. SuperPower, Inc. has a program with the U.S. Air Force to produce a filamentary YBCO conductor for ac applications (discussed later).

YBCO Conductor Development

Because YBCO-coated conductors are now made reel to reel in hundreds of meters length, research and development needs to shift toward improving the conductor and applying the conductor to the variety of applications it has. This does not mean that additional improvements to the basic conductor architecture are not necessary or possible. In the discussion that follows, emphasis will be on improvement of the YBCO-coated conductor as opposed to developmental issues to apply the conductor to an application, that is winding issues, and so forth. The ac loss section will include a couple of

lessons learned from past programs. Again, this paper specifically addresses Air Force programs and concerns.

As a note, the primary generator designs that have been used to date, including the recently mentioned GE approach, is where only the field windings for the rotor use superconductors. The stator uses conventional copper windings. If the rotating machine, such as the generator, is fully superconducting both field and armature windings, then differences may exist in how the supercurrents flow in the conductor for the parts. Indeed, Carr^{9,10} has developed a theory for an all-superconducting electric generator based on Maxwell's equations. This theory based on an HTS-coated conductor for the armature winding differs significantly from that used for a normal generator. In his theory, the importance of surface charges on the superconductor is a central feature.

Pinning

An important parameter for enabling superconducting generator operation at the higher temperatures of liquid nitrogen is increasing J_c , or more importantly J_e . J_e is defined as the operating current divided by the total cross section of the whole wire, which includes the nonsuperconducting portions of the tape and the insulation. Reducing the substrate thickness can increase J_e , as an example, but thicker YBCO layers and/or higher J_c will be the primary research focus because minimum thicknesses of the nonsuperconducting portions will be necessary for mechanical strength, adequate dielectric properties, and so on. Another consideration is the angular dependence of the YBCO-coated conductor. Because YBCO is anisotropic, J_c can decline by an order of magnitude when going from the a,b -axis magnetic field orientation to the c -axis orientation.

In the area of pinning enhancement, nanoparticle pinning of the YBCO has demonstrated the best performance improvements. The J_c can be greatly increased in the YBCO films by the intentional addition of a high density of nanoparticles to the superconductor itself to act as 3-D pinning centers. Nanoparticle dispersions have been accomplished by a variety of methods,^{11–16} being first demonstrated by Haugan *et al.*¹⁷ The nanoparticulates must be well dispersed and should occupy <15% of the superconductor's volume. The primary problem with these demonstrations of nanoparticle pinning is that the techniques used to create the nanoparticles do not directly apply to the processing methods used by industry. Recent work

has demonstrated the Ca-doped nanoparticles can provide improvements over and above those given by the nanoparticles themselves.

One effort of the Air Force programs is to find alternate means to incorporate these pinning centers, which is amenable to industrial processes. One example is minute doping by the incorporation of very minor additions ($\leq 1\%$ of Y) of typically deleterious rare earths into high-quality $YBa_2Cu_3O_{7-\delta}$ thin films to bring about improvement in the film's in-field current density.¹⁸ In this work, it was accomplished without reoptimization of the deposition parameters. Instead of typical site substitution for Y , the deleterious rare earths seem to form nanoparticulates, explaining the enhanced performance over standard rare-earth substitutions by the preferred elements. Figure 2 displays some representative data of the improvement in the YBCO conductor. Figure 2a shows the relative enhancement normalized to the plain YBCO curve for a variety of dopants, and Fig. 2b displays a comparison of different doping concentrations of Tb.

Another important aspect is finding a better nanoparticle. A recent discovery by Varanasi *et al.*¹⁹ is BaSnO₃ nanoparticle pinning which seems to have superior properties of BZO and Y211. When determining the extent and nature of the pinning provided in pinning force plots, it is the irreversibility field, H_{irr} , the maximum of the bulk pinning force curve, $F_{p,max}$, relative to the irreversibility curve, and the shape of the curve that primarily matter. With nanoparticles of BaSnO₃ introduced into YBCO films using a dual sector-pulsed laser ablation target of the two materials, it was demonstrated that $F_{p,max}$ can exceed half of H_{irr} as opposed to the typical $\sim 0.3 H_{irr}$. Additionally, the H_{irr} was greater than typically pinned YBCO. The low-temperature superconductors (LTS), for example NbSn and NbTi, have demonstrated that $F_{p,max}$ can occur at $b = 0.6$ where $b = H/H_{c2}$,^{1,2} but HTS materials have only approached the halfway point in some pinned bulk materials that have significantly lower critical currents.²⁰

AC Loss

AC losses result in a YBCO-coated conductor as a result of either applying ac currents to the conductor (such as the beam spreader magnets) or placing the conductor in applied alternating magnetic fields (such as with the generator). Minimizing these losses entails re-

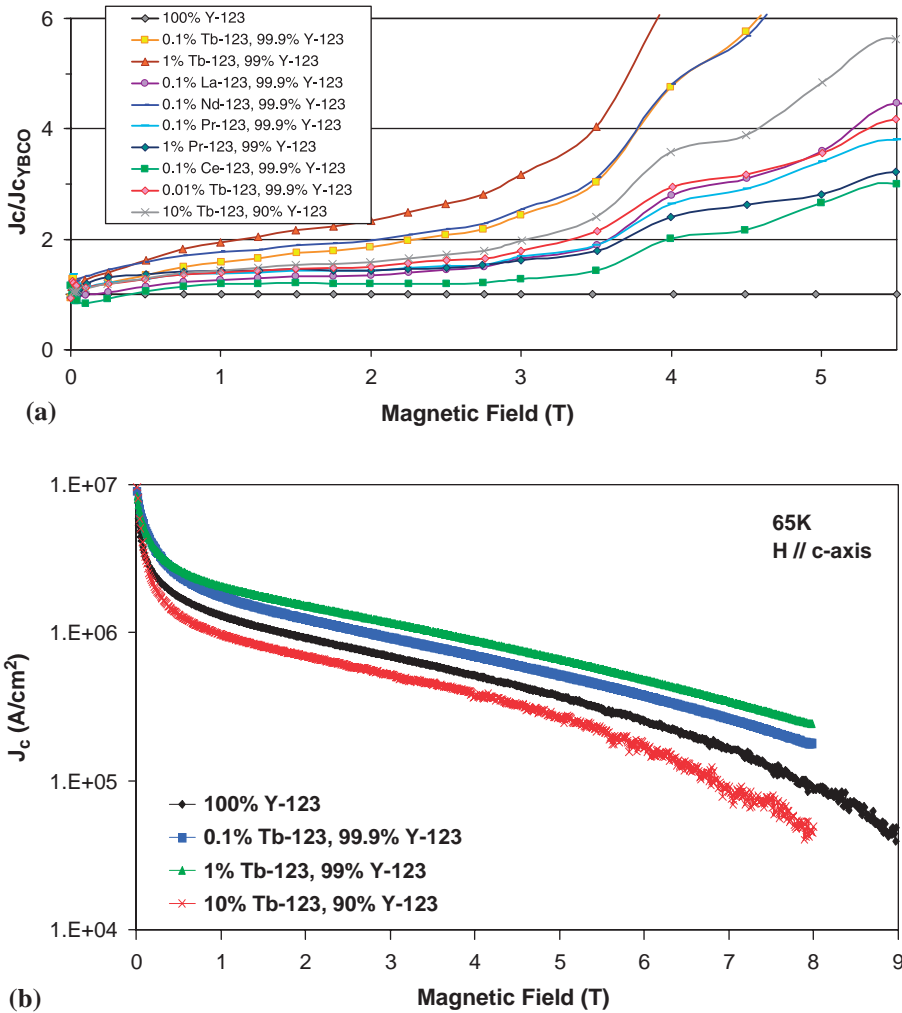


Fig. 2. Minute doping improvements to $YBa_2Cu_3O_{7-x}$ (YBCO) thin films: (a) displays data at 77 K (H parallel to c -axis) of the improvement to the YBCO conductor for a variety of dopants—data are normalized to the control YBCO curve; (b) displays a comparison of different doping concentrations of Tb at 65 K.

duction of hysteretic losses in the superconductor, normal metal effects such as eddy currents, ferromagnetic substrate contributions, and coupling current losses. Depending on the application environment, certain types of these losses will dominate. A principal concern is the hysteretic loss, but the other losses can become quite important, especially at high frequencies inherent in airborne generator designs. Successful incorporation of HTS conductor into these applications will require the development of an ac-tolerant version of the YBCO-coated conductor that will sufficiently minimize these effects.

In the field windings, the superconductor will experience mostly a dc field, but ac asynchronous feedback on the winding will induce losses there. The most severe environment for ac loss is if the armature windings of the generator are made superconducting in a fully superconducting generator. The case of the armature windings is often mentioned because it is the most severe requirement, and a conductor meeting this requirement will readily meet most other applications. One of the first U.S. Air Force generator designs was an all-cryogenic, superconducting system designed by Dynatech back in 1967.²¹ The generator was not

successful due to the large ac losses in the superconducting armature winding. Closer at hand is the ac issue in the field windings. Shielding must be added to protect them from ac losses; however, it would be better to tailor the conductor to fit in the generator than to tailor the generator to accept the conductor. This issue was highlighted in a U.S. Air Force contract with Westinghouse to build a 5 MVA, 400 Hz machine where the electromagnetic shield on the rotor was considered to be the most significant problem of the superconducting alternator. Excessive heating in the shield was a consequence of the load-induced varying fields, leading to the suggestion that future designs have separate thermal and electromagnetic shields to avoid the issue.²² A more ac-tolerant YBCO conductor may potentially eliminate the shielding requirement, if not just reduce the amount of shielding.

Initial means have been developed to reduce the ac losses, but more must be done and does not preclude alternate more effective developments. Ferromagnetic loss of the substrate can be removed by avoiding the use of these materials. Reduction of hysteretic losses can be brought about by making the coated conductor with a filamentary design and making the filament width very narrow.^{23–25} Eddy currents and coupling currents can be reduced by increasing the resistance of the substrate and interfilamentary path, respectively. Twisting (or some scheme to allow field penetration), whether in the YBCO-coated conductor architecture or of the conductor itself, is necessary. An important point that is sometimes not clear in data presentation of losses is that instead of considering particular frequencies at particular magnetic fields, the sweep rate of the applied magnetic field can be used. Levin *et al.*²⁶ devised a scaling that allows the contributions of the hysteresis and coupling losses to be quantified in terms of the sweep rate and allows ready differentiation of the two types of losses, which tend to be the primary losses.

The results of the experimental data can be readily extrapolated beyond the envelope of accessible field amplitude and frequency, but care must be taken in that extrapolation too far may be meaningless. Data are often taken at lower magnetic field values and sweep rates where the theory may be different in the stronger fields associated with rotating machinery.⁸ This naturally implies that thorough modeling of the situation is important. In addition, measurements must be made on long conductors and windings and must be made at higher field sweep rates, or higher magnetic fields and

frequencies. Some initial measurements have been made on small coils, but where the ac current is applied as opposed to being induced by an alternating magnetic field.²⁷ In this case, the properties were measured of a small pancake coil made with a 10 mm wide copper-stabilized YBCO-coated conductor. When the radial component of the magnetic field was mapped at the coil edge, it differed from that determined from a uniform current distribution. In addition, the ferromagnetic properties of the substrate had a clear effect on the coil as evidenced by the observed hysteresis.

New measurement techniques to understand the fundamental nature of the ac currents in the YBCO-coated conductor can be very useful. Just recently, Lucarelli *et al.*²⁸ demonstrated time-resolved magneto-optical (MO) imaging of a YBCO film in a high-frequency alternating current (ac) regime. This particular setup allowed the evolution of the magnetic flux distribution in YBCO samples to be studied as a function of the phase of the applied ac current. An important experimental evidence was given to what degree the ac current density maximum shifts in from the edges of the sample caused by the higher self-induced field in that region.

Other recent progress has been made with the multifilamentary structure for the YBCO conductor. A simple experimental approach was reported to reduce the coupling losses resulting from the interfilamentary connection via the substrate when ablated metal from a laser striation process provides the connection.²⁹ When the substrate metal in the grooves segregating the filaments is exposed to oxygen, it forms an oxide that electrically insulates the filaments from each other. An interfilamentary current-sharing scheme has also been devised to facilitate current transfer between filaments to circumvent blockages or breaks in the filaments.³⁰ This was done using a sparse network of superconducting microbridges that was superimposed on the striated film, but that did not substantially increase the magnetization losses.

Scaling the filamentary structure to longer lengths must occur in order to begin winding demonstration of the ac-tolerant version of the YBCO conductor. A U.S. Air Force program with SuperPower Inc., is underway to do this very thing. Construction of a reel-to-reel photolithography striation system is being carried out to create the filamentation in the YBCO. This system provides narrow grooving to minimize loss of conductor. Figure 3 shows a 4 mm wide tape that was patterned by photolithography to yield 100 μm conductor filament

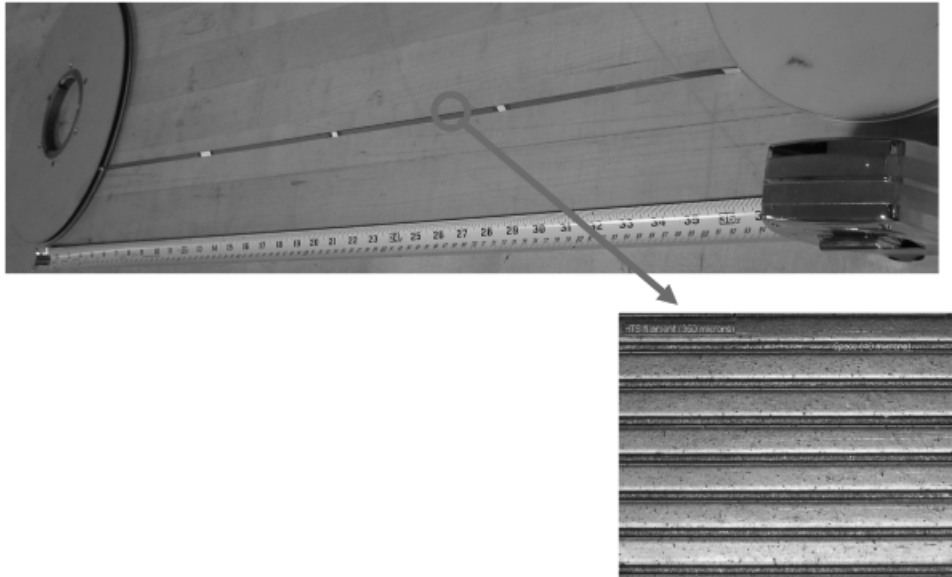


Fig. 3. A 1 m by 4 mm striated conductor produced by reel-to-reel photolithography. Image is provided by SuperPower Inc.

widths with a 25- μm spacing. A 12 mm tape can be patterned and subsequently slit to a 4 mm width or patterned after slitting the original tape even down to 2 mm. Also demonstrated so far during the program is twisting of the tape where 95% of the original critical current was retained at a 9.4 cm twist pitch and lower ac losses were demonstrated with a stack of two 2 mm wide striated tapes compared with a single 4 mm wide striated tape. Figure 4 shows that not only is the YBCO film striated, but the copper-stabilizing layer is as well to reduce the attendant coupling and eddy current losses.

Stability and Quench

With longer lengths of the YBCO conductor at hand and programs starting to appear to implement the

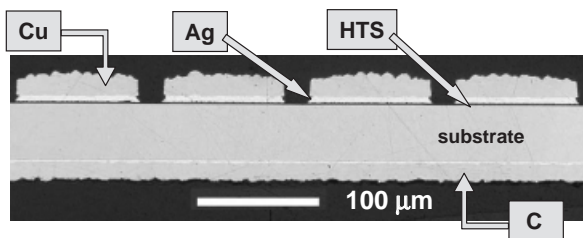


Fig. 4. Cross-sectional view of a striated $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ YBCO-coated conductor displaying a filamented stabilizing layer on top of the YBCO.

conductor, stability, and quench issues are now an important consideration to address. Because of the possibility of quench, the conductors must be protected so that in case a quench does occur, the windings are not irreparably damaged. HTS conductors at 77 K have a much greater intrinsic stability margin than an LTS conductor, making a quench less likely, but can still occur. In a fully cryostable operation, the current is transferred to the stabilizer during a quench and the heat generated in the stabilizer is fully removed by heat transfer to the cryogenic bath. Because of this, better materials or architectural redesign of the conductor can improve the stability. Improvement of the normal zone propagation will require the use of insulating materials with high thermal conductivity but low electrical conductivity. Thermal contact throughout the YBCO conductor architecture is desired. The concept of the conductor being surrounded by a stabilizing layer³¹ can be useful in promoting both the radial and transverse spread of heat.

Summary

Superconducting components made using a YBCO conductor can enable megawatt-class power airborne systems due to the reduction in size and weight over the conventional counterparts. A directed energy applica-

tion, active denial technology, was given as an example of the present programs. YBCO-coated conductors can be further enhanced by better magnetic flux pinning processes and development of an ac-tolerant version of the conductor. Improvements in these areas as well as better stability will lead to unprecedented power densities for military applications.

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